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Extra light fermions in E_6 -inspired models and the 3.5 keV X-ray line signal

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Abstract

We propose a scenario in which extra light fermions in an E_6 -inspired U(1) extension of the standard model constitute the dark matter, as a simple variation of our model for dark radiation presented in 2010. Interestingly, for the light fermions of mass about 7 keV, they radiatively decay into active neutrinos and photons with a lifetime in the range of $10^{27} - 10^{28}$ seconds, which naturally explains the recently discovered 3.5 keV X-ray line signal.

Recently two groups independently reported detection of an unidentified X-ray line at about 3.5 keV in the XMM-Newton X-ray observatory data of various galaxy clusters and the Andromeda galaxy [1, 2]. The observed X-ray line could be due to decaying dark matter (DM), although there are a variety of systematic uncertainties that might affect the observed line energy and flux. In this Letter we pursue a possibility that decaying dark matter of mass about 7 keV explains the excess of the X-ray line at 3.5 keV.

One of the plausible candidates for light decaying dark matter is sterile neutrinos [3, 4, 5]. See Refs. [6, 7, 8] for a review on sterile neutrino dark matter and its various implications. Sterile neutrinos radiatively decay into neutrinos and photons via their mixings with the active neutrinos. The mass and the lifetime of the sterile neutrino dark matter preferred by the observed X-ray line excess are [1, 2].

$$m_{\text{DM}} \simeq 7 \text{ keV}, \quad (1)$$

$$\tau_{\text{DM}} \simeq 2 \times 10^{27} - 2 \times 10^{28} \text{ sec}, \quad (2)$$

where the total dark matter is assumed to be made of the sterile neutrinos. Such extremely light sterile neutrino together with other two heavy right-handed neutrinos can be realized in an extra dimensional set-up [9], while retaining the seesaw formula [10]. It has been known, however, that such light sterile neutrino should not contribute to the light neutrino mass through the seesaw mechanism in order to satisfy the existing X-ray bounds [11, 12]. Indeed, the lifetime would be several orders of magnitude shorter than the required value (2) for the sterile neutrino mass 7 keV [13], which signals the necessity for some extension such as extra flavor structure.¹ In particular, the fact that the sterile neutrino dark matter should not contribute to the light neutrino mass through the seesaw formula suggests that it might have a different origin from that of the heavy right-handed neutrinos.

In this short Letter we propose an alternative to the right-handed sterile neutrino dark matter, as the origin of the 3.5 keV X-ray line. We explore the possibility that extra light fermions in an extension of the standard model (SM) gauge group become dark matter which decays into photons explaining the observed X-ray line excess. Intriguingly, we

¹ Another possibility is to introduce a set of chiral fermions charged under $U(1)_{B-L}$, where the number and the charge assignment are tightly constrained by the anomaly cancellation, and at least five additional chiral fermions are necessary [14]. For one of the solutions, the lightest chiral fermion becomes naturally as light as $\mathcal{O}(\text{keV})$ and may decay into neutrinos and photons if $Z_2(B-L)$ is approximate.

SU(5)	U(1) _{ψ}	U(1) _{B-L}	Z ₂
$\psi_{\mathbf{10}}^{(\text{SM})}$	1	1	even
$\psi_{\mathbf{\bar{5}}}^{(\text{SM})}$	1	-3	even
$\psi_{\mathbf{1}}^{(\text{SM})} \equiv \nu_{\text{R}}$	1	5	even
$\psi_{\mathbf{5}}$	-2	-2	odd
$\psi_{\mathbf{\bar{5}}}$	-2	2	odd
$\psi_{\mathbf{1}} \equiv \psi$	4	0	even
$\phi_{\mathbf{1}} \equiv \phi$	1	5	even
$\phi_{\mathbf{5}} \supset H$	-2	-2	even
$\phi_{\mathbf{\bar{5}}} \supset \bar{H}$	-2	2	even
$X_{\mathbf{1}} \equiv X$	n	0	even

Table 1: Notation and charge assignments on the fields in the E_6 -inspired model.

shall see that the lifetime falls in the right range of (2) for the given dark matter mass of 7 keV.

Let us consider an E_6 -inspired extension of the SM, based on the model for dark radiation proposed by the present authors in 2010 [15]. Here we consider a gauge group of two additional anomaly-free U(1)s, $\text{SU}(5) \times \text{U}(1)_{\psi} \times \text{U}(1)_{\text{B-L}}$, inspired by the E_6 model of the GUT [16].² Here SU(5) includes the SM gauge groups. The E_6 group has a **27** representation, which can be decomposed as $\mathbf{27} = (\mathbf{10} + \mathbf{\bar{5}} + \mathbf{1})_{\mathbf{1}} + (\mathbf{5} + \mathbf{\bar{5}})_{-\mathbf{2}} + \mathbf{1}_{\mathbf{4}}$ in terms of the SU(5) representation, where the subscript denotes the U(1) _{ψ} charge. See Table 1 for notation and charge assignments. All the SM fermions plus a right-handed neutrino in one generation are contained in the first multiplet. On the other hand, there are extra fermions, $\psi_{\mathbf{5}}$, $\psi_{\mathbf{\bar{5}}}$ and $\psi_{\mathbf{1}}$, in the **27** representation, where the subscript indicates the representation under SU(5). The SM gauge singlet fermion, $\psi_{\mathbf{1}}$, is a candidate for dark radiation or light dark matter [15].

We introduce two SM-singlet Higgs fields: ϕ and X , whose vacuum expectations values (VEVs) induce the spontaneous breaking of the two U(1)s. See Table 1 for their charge assignments. First, the VEV of ϕ breaks a combination of two U(1)s, giving rise to the

² Here the charge assignment of the U(1)_{B-L} is given by a certain combination of the U(1) hypercharge and the B - L.

right-handed neutrino mass as

$$\mathcal{L} = \frac{1}{2M} \langle \phi^* \rangle^2 \nu_R \nu_R + \text{h.c.}, \quad (3)$$

where M denotes the cutoff scale. The right-handed neutrino mass will be about 10^{15} GeV for $\langle \phi \rangle \sim 5 \times 10^{16}$ GeV and $M = M_P \simeq 2.4 \times 10^{18}$ GeV, and the light (active) neutrino masses can be explained by the seesaw mechanism [10]. Note that the other combination, $U(1)_X \equiv 5U(1)_\psi - U(1)_{\text{B-L}}$, remains unbroken, and fermions except for ν_R do not get masses by the VEV of ϕ . We also impose a Z_2 parity (see Table 1) to forbid a mixing between extra colored fermion and SM fermions, $\mathcal{L} = \phi \psi_{\mathbf{5}}^{(\text{SM})} \psi_{\mathbf{5}} + \text{h.c.}$. Also the interactions with the Higgs fields $\phi_{\mathbf{5}}$ and $\phi_{\bar{\mathbf{5}}}$ and the extra fermions, $\phi_{\mathbf{5}} \psi_{\bar{\mathbf{5}}} \psi_{\mathbf{1}}$ and $\phi_{\bar{\mathbf{5}}} \psi_{\mathbf{5}} \psi_{\mathbf{1}}$, are forbidden.

Secondly, the remaining $U(1)_X$ is broken by the VEV of the other SM-singlet Higgs, X , whose $U(1)_\psi$ charge is represented by n . If $n = 4$, both ϕ and X are a part of the **27**-plet in the E_6 . To be more general, however, here we allow n to take a different value. The mass of ψ is generated through

$$-\mathcal{L} = \frac{1}{2} M \left(\frac{\langle X^* \rangle}{M} \right)^{8/n} \psi \psi + \text{h.c.} \quad (4)$$

Thus the possible value of n is $n = 1, 2, 4, 8$. Among these, $n = 8$ requires a very small VEV of X for generating small ψ mass. In the following we consider the cases of $n = 4$ and $n = 1$. The situation for $n = 2$ lies between these two cases. After X develops a non-zero VEV, ψ obtains a mass of

$$m_\psi \simeq \begin{cases} 7 \text{ keV} \left(\frac{\langle X \rangle}{4 \times 10^6 \text{ GeV}} \right)^2 \left(\frac{M_P}{M} \right) & \text{for } n = 4 \\ 7 \text{ keV} \left(\frac{\langle X \rangle}{2.8 \times 10^{15} \text{ GeV}} \right)^8 \left(\frac{M_P}{M} \right)^7 & \text{for } n = 1. \end{cases} \quad (5)$$

This light fermion may act as the DM in the universe.³ The other extra fermions, $\psi_{\mathbf{5}}$ and $\psi_{\bar{\mathbf{5}}}$, obtain the Dirac mass through

$$-\mathcal{L} \simeq M \left(\frac{\langle X \rangle}{M} \right)^{4/n} \psi_{\mathbf{5}} \psi_{\bar{\mathbf{5}}} + \text{h.c.} \quad (6)$$

³ We can also write down the ψ - ν_R mixing term, $\mathcal{L} \sim (X^*)^{4/n} \phi^* \psi \nu_R / M^{4/n} + \text{h.c.}$, but inclusion of this term does not much affect the result.

Thus its mass is given by $\sqrt{m_\psi M} \sim 4 \times 10^6 \text{ GeV}$ for $m_\psi = 7 \text{ keV}$ and $M = M_P$. Note that the mass is independent of n for the given m_ψ .

The mixing between active neutrinos and ψ allows ψ to decay into the neutrino and photon, similarly to the sterile neutrinos. The mixing arises from the operator

$$-\mathcal{L} = c \left(\frac{\langle \phi \rangle}{M} \right) \left(\frac{\langle X^* \rangle}{M} \right)^{4/n} H L \psi + \text{h.c.}, \quad (7)$$

where H is the SM Higgs doublet and L is the lepton doublet and c is a numerical constant of order unity. The mixing angle between ψ and active neutrinos, θ , can be evaluated as

$$\theta \simeq c \left(\frac{\langle \phi \rangle}{M} \right) \left(\frac{v}{M} \right) \left(\frac{\langle X \rangle}{M} \right)^{-4/n} \simeq \frac{c \langle \phi \rangle v}{m_\psi^{1/2} M^{3/2}} \quad (8)$$

$$\simeq 9 \times 10^{-7} c \left(\frac{\langle \phi \rangle}{5 \times 10^{16} \text{ GeV}} \right) \left(\frac{7 \text{ keV}}{m_\psi} \right)^{1/2} \left(\frac{M_P}{M} \right)^{3/2}, \quad (9)$$

where $v = 174 \text{ GeV}$ is the VEV of the SM Higgs and we have omitted $\tan \beta$ for simplicity. Most important, this value of the mixing is close to the value required to explain the excess of the 3.5 keV X-ray line: $\theta \sim 4 \times 10^{-6}$ [2]. Note that the mixing is independent of n for the given mass of ψ . Thus, the required longevity (2) is automatic in our model.

The abundance of ψ depends on thermal history of the universe. For high enough reheating temperature after inflation, ψ is thermalized through $U(1)_X$ gauge interactions. The freezeout temperature of ψ is estimated to be $T_f \sim (\langle X \rangle^4 / M_P)^{1/3} \sim \mathcal{O}(100) \text{ GeV}$ for $\langle X \rangle \sim 10^6 \text{ GeV}$ ($n = 4$) and $T_f \sim 10^{14} \text{ GeV}$ for $\langle X \rangle \sim 10^{15} \text{ GeV}$ ($n = 1$) for the $U(1)_X$ gauge coupling constant of $\mathcal{O}(1)$. Assuming that three generations ψ all have equal masses for simplicity, we obtain the relic abundance as

$$\frac{\rho_\psi}{s} \simeq 8 \times 10^{-8} \text{ GeV} \left(\frac{m_\psi}{7 \text{ keV}} \right) \left(\frac{106.75}{g_{*s}(T_f)} \right), \quad (10)$$

if the reheating temperature is higher than the freeze-out temperature, i.e., if they are thermalized. Here $g_{*s}(T_f)$ counts the relativistic degrees of freedom at the freeze-out. If ψ particles are thermalized, we need a dilution factor of ~ 200 in order to obtain correct relic DM abundance. Suppose that the reheating temperature is so high that the extra heavy fermions, $\psi_{\mathbf{5}}$ and $\psi_{\bar{\mathbf{5}}}$, are also efficiently produced. This is indeed the case of $n = 1$ as the freeze-out temperature is higher than the mass of $\psi_{\mathbf{5}}$ and $\psi_{\bar{\mathbf{5}}}$. They are stable in

the presence of the exact Z_2 symmetry, but they decay into SM particles if the Z_2 parity is weakly violated. For a certain breaking of the Z_2 symmetry, the decay could produce the required entropy production to obtain the right DM abundance of ψ [17]. Alternatively, if the reheating temperature is slightly lower than the freeze-out temperature, a correct amount of DM can be produced.

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